Rare Decays of Heavy Flavor

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***For* B Group**

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FNAL

Outlines

- Overview of Motivations
- Rare Charm decays
  - Method
  - FCNCs
    - $D^0 \rightarrow \mu^+\mu^-$
    - $D^+ \rightarrow l^+l^-\pi^+$, $D^+_s \rightarrow l^+l^-K^+$
  - Others ($FCNC^2$, LFV,LNV) $D_x \rightarrow llh$
  - $D^0 \rightarrow K^+\pi^-$
- Rare B decays
  - Method
  - FCNCs
    - $B_{s(d)} \rightarrow \mu^+\mu^-$
    - $(B/B_s/B+/\Lambda_b) \rightarrow l^+l^-h$
  - Others ($FCNC^2$, LFV,LNV) $B_x \rightarrow llh$
- Prospects
- Summary

Motivations (considering H→llh modes only)

- Motivated by probing for New Physics
- Search/constraints on FCNC decays is a remarkable tool in a search/constraint of New Physics
  - Charm FCNCs are c→u transition
    - Relatively small interest due to GIM suppression
  - B-FCNCs are (most often) b→s transition
    - b→s γ has been a NW search and constraint workhorse for years
      - ✓Now at a (brick?) wall due to systematics in both experiment and theory
    - b→s $\mu^+\mu^-$ for B-mesons and Λ_b has a potential of probing NP via shape analysys [m($\mu^+\mu^-$) or (a)symmetry]
    - B_s→ $\mu^+\mu^-$ has a strong NP probe potential once the experimental sensitivity is available
- Probing other processes, like
  - double-FCNC ($FCNC^2$) -- more "rare" than FCNC and the benefit is smaller
  - lepton flavor/number violation – none in SM (0 uncert) →if seen → NP
- CDF has a substantial sensitivity to exclusive (dilepton [e,μ]) B and Charm modes

Rare Charm decays

- FCNCs are GIM suppressed in SM
  - Long-range effects (decays via resonances) dominate the Bratio
- Up-to expt values are possible in R-parity violating SUSY or some non-universal SUSY scenarios

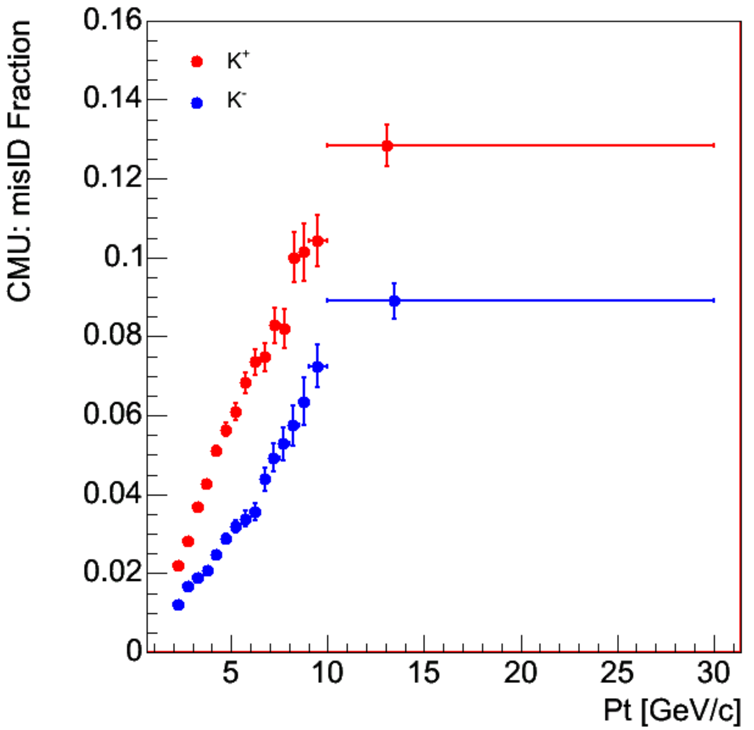
- FCNCs
  - $D^0 \to \mu^+\mu^-$
  - $D^+ \to l^+l^-\pi^+$, $D^+_s \to \mu^+\mu^-K^+$
- Others ($FCNC^2$, LFV,LNV) $D_x \to llh$

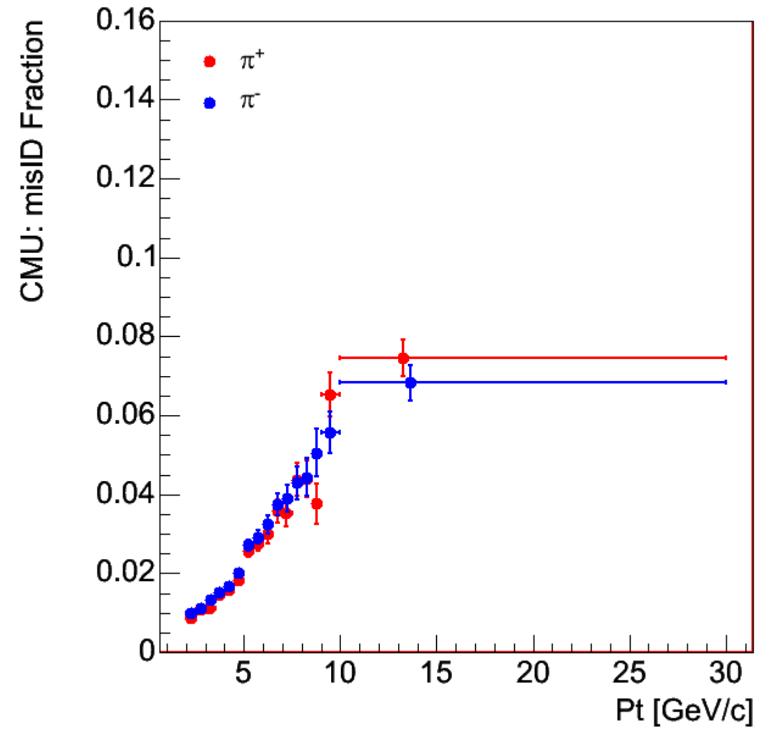
Experimental method:

- Take a $D \to hh$ or $D \to hhh$ as normalization mode with a D^*-tag
  - Signal mode naturally comes in the same sample
  - Normn Bratios are large due to large V_{cs} and V_{cd}
- Get "peaking" N_{bg} by applying $h \to \mu$ fake rates
  - $h=\pi \to \mu$ gives the best match in mass ($m_\mu \approx m_\pi$)
- Get "flat" N_{bg} from sidebands
- "Unblind" by looking at lepton ID

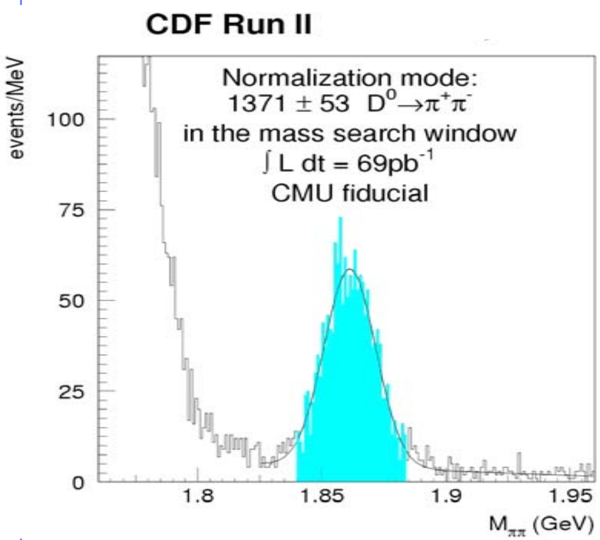
Fake rates K,$\pi \rightarrow \mu$

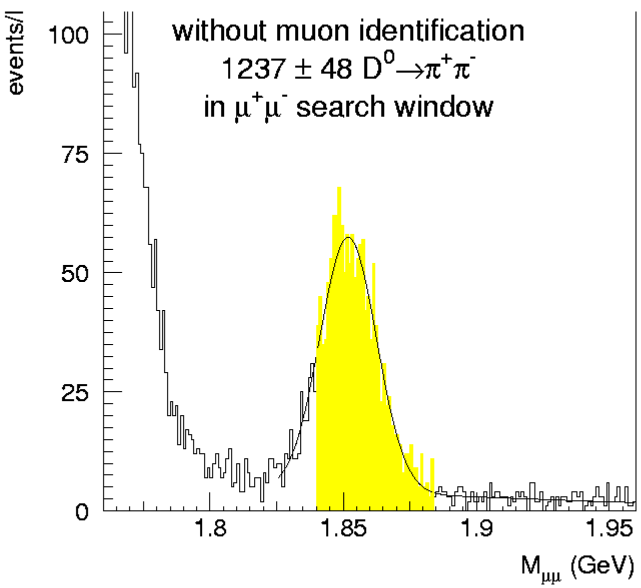
- Substantial progress since the measurement of $D \rightarrow \mu\mu$ with 69 pb^{-1}
  - Thanks to E. Berry, I. Furic, et al.
    - The rates are measured from $D^* \rightarrow \pi\ D(K\pi)$ sample for CMU, CMP, CMX
    - The precision allows for parameterization in 1+ variables (e.g., not p_T only)
- Fake rates are essential for rare D-decays
  - Less so for rare B-decays due to smaller $B \rightarrow hh$ Bratios [$\sim (V_{cb}/V_{cs})^2 \sim 0.01$ suppression]
    - Can become essential for $B \rightarrow \mu\mu$ due to its small value and good exp sensitivity





$D^0 \to \mu\mu$ search (69 pb^{-1})





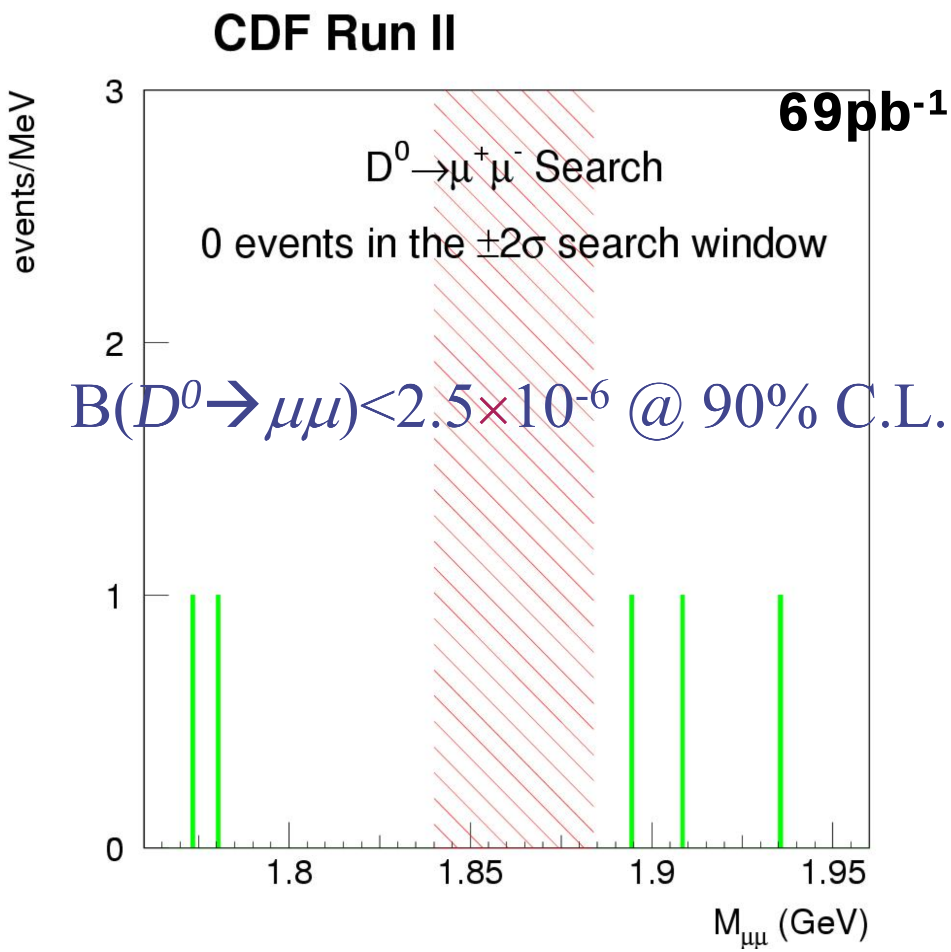
- Use $D^{*\pm} \to D_0\pi^{\pm}$ tagged events
- Use $D_0 \to \pi^+\pi^-$ as a normalization mode.
  - Blind from μID in $1.840 < m_{\mu\mu} < 1.882$ GeV
- Cuts:
  - $|d_0(\mu,\pi)| > 120\mu m$, $|d_{xy}(D_0)| < 150\mu m$
  - $\Delta\varphi(\mu\mu) > 0.085$
- Background:
  - combinatorial (from right sideband) – expect 1.5±0.7
  - misID – expect $N(D_0 \to \pi^+\pi^-) \times P(\text{misID})^2 \approx 0.3 \pm 0.1$

$$Br(D^0 \to \mu\mu) \le \frac{N_{CL}(D^0 \to \mu\mu)}{N(D^0 \to \pi\pi)} \underbrace{\frac{\varepsilon(D^0 \to \pi\pi)}{\varepsilon(D^0 \to \mu\mu)}}_{\approx 1.012} \underbrace{Br(D^0 \to \pi\pi)}_{\approx 1.43 \cdot 10^{-3}}$$

$D^0 \rightarrow \mu\mu$ search

- Latest result from BaBar is $B(D^0 \rightarrow \mu\mu) < 1.3 \times 10^{-6}$ @ 90% C.L.
  - cf. $Br_{SM} \sim 10^{-13}$

- With 1 fb^{-1} expect *~×10-20* improvement (to $\sim 1 \times 10^{-7}$)
  - More data and now cover CMX



$B(D^0 \rightarrow \mu\mu) < 2.5 \times 10^{-6}$ @ 90% C.L.

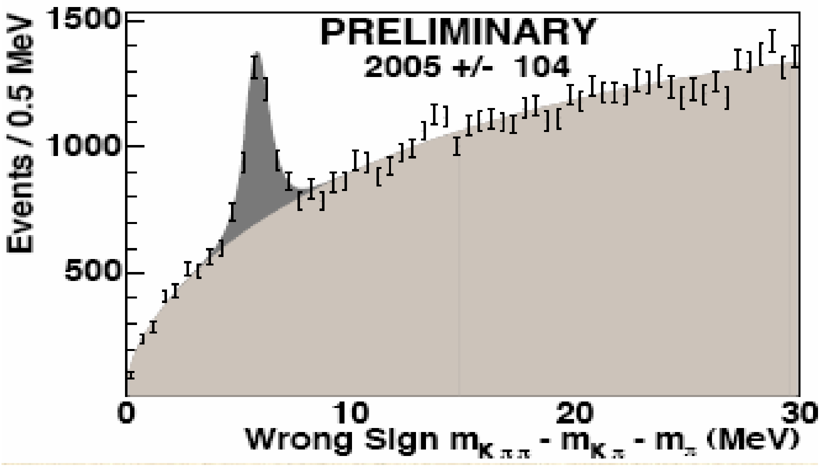
$D^+/D_s^+ \rightarrow$ llh searches

- Only very rough estimates now
  - Straightforward to address $D_x \rightarrow \mu\mu h$ models
  - Need to measure $h \rightarrow e$ fake rates to use for remaining dilepton modes
    - Work in progress by R. Harr and D. Dhaliwal
- With 1 fb^{-1} should be able to achieve sensitivity comparable/better than currently available (PDG $\leftarrow$ BaBar/Cleo-c/Belle/Hera-B)

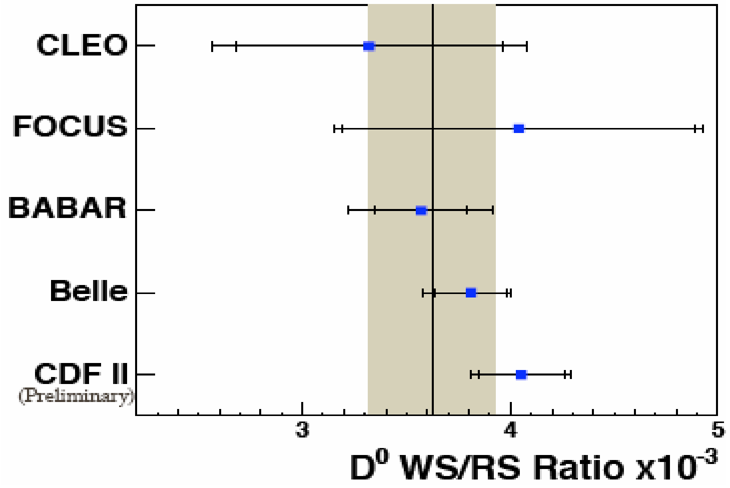
$D^0 \to K^+\pi^-$

M. Mattson and P. Karchin

- $D^0 \to K^+\pi^-$ is (mostly) double Cabibbo-suppressed (DCS) decay
  - Compared to $Br(D^0 \to K^-\pi^+)$:$Br(D^0 \to K^+\pi^-)$~$(V_{cs}V_{ud})^2$: $(V_{cd}V_{us})^2$
  - Can also proceed via D^0—D^0bar mixing
    - ✓$Br(D^0 \to K^+\pi^-) < 1.6\times10^{-5}$ @95% CL (CLEO-2)
  - ➢$Br(D^0 \to K^-\pi^+)=3.81\pm0.09$ % $Br(D^0 \to K^+\pi^-)=(1.38\pm0.11)\times10^{-4}$ (PDG: mostly BaBar)
- Measure R=WS/RS=$Br(D^0 \to K^+\pi^-)$:$Br(D^0 \to K^-\pi^+)$ [time integrated]
  - WS/RS=0.362±0.029% (PDG)
  - Use π charge from D^* ($D^{*+} \to \pi^+D^0$ or cc) to tag D^0/anti-D^0
  - Vtx cuts, remove M_{RS}~M_{WS}, use dE/dX
- (unblinded, ~ blessed) WS/RS=0.405±0.021±0.012% = 0.405±0.024%



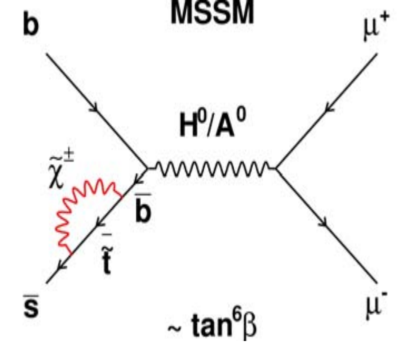
350 pb^{-1}



Improve uncert-ty by ~50% with $1fb^{-1}$

Rare B-decays

- FCNCs are suppressed in SM
  - Much softer suppression than in D→llh
- The leading modes probe b→s transition in many aspects
- Up-to expt values are possible in
  - R-parity violating SUSY
  - numerous SUSY scenarios with large tanβ



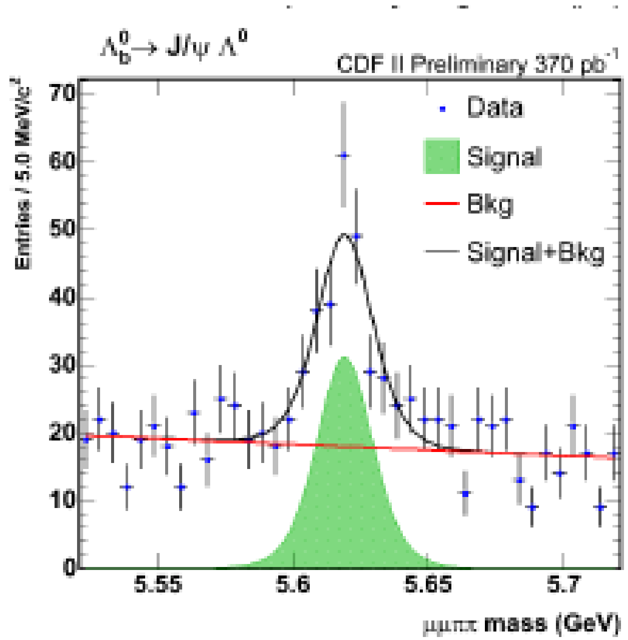
- FCNCs
  - $B_{s(d)} \to \mu^+\mu^-$
  - $(B/B_s/B+/\Lambda_b) \to l^+l^-h$
- (FCNC², LFV,LNV, etc) $B_x \to llh$

Experimental method:

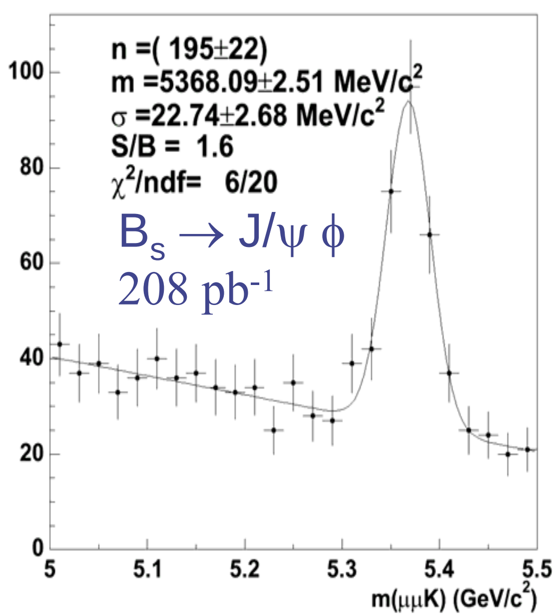
- Take $B/B_s/B^+/\Lambda_b \to J/\psi\ h$ as normalization mode
  - Signal mode naturally comes in the same trigger sample
  - Normn Bratios are relatively large
- B→μμ uses RAREB (no SVT/LXY) and B→μμh use RAREB LXY trigger
  - Due to mass selections in noSVT/LXY triggers
- Get "flat" N_{bg} from sidebands (bgd is mostly combinatoric)
  - Discriminate based on vertex and dilepton ID
  - Use uncorrelated disc variables to factorize bgd cut power to improve statistics
  - Use either a likelihood or a box cut
- Optimize on expected Bratio ($\sim S/B^{1/2}$) for a limit (measmnt)
- "Unblind" by looking inside the mass window

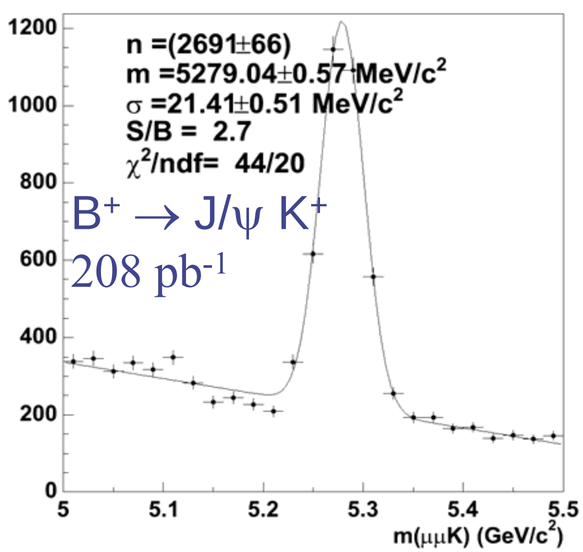
Normalization modes for B-FCNCs

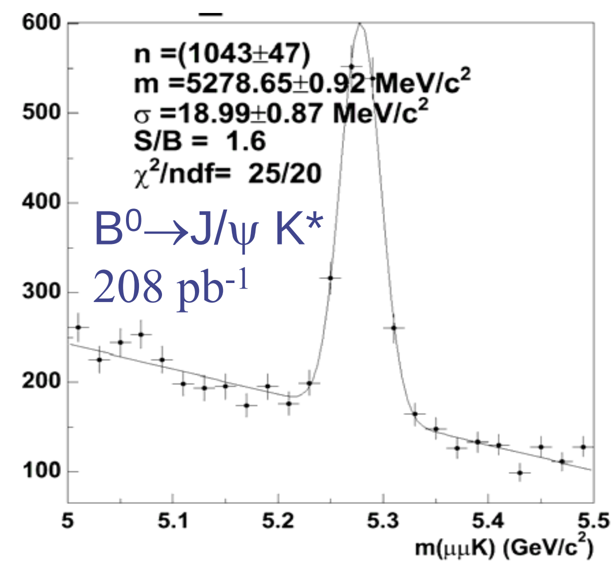
- $H_b \rightarrow J/\psi h$ mode correspond to $H_b \rightarrow \mu^+\mu^- h$
- Using dimuon normalization modes greatly reduces systematics
  - $B^+ \rightarrow J/\psi K^+$ is also used for $B_{s(d)} \rightarrow \mu^+\mu^-$



S. Farrington and R. Oldeman







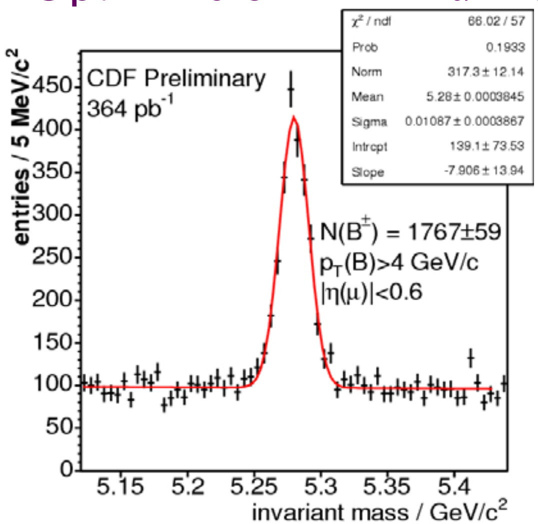
$B_{s(d)} \rightarrow \mu^+\mu^-$ Ingredients

- Normalize to $B+ \rightarrow J/\psi\ K^+$ decays

$$BR(B_s \rightarrow \mu^+\mu^-) = \frac{N_{Bs}}{(\alpha\varepsilon)^{total}_{Bs}} \frac{(\alpha\varepsilon)^{total}_{B+}}{N_{B+}} \frac{f_u}{f_s} BR(B^+ \rightarrow \mu^+\mu^- K^+)$$

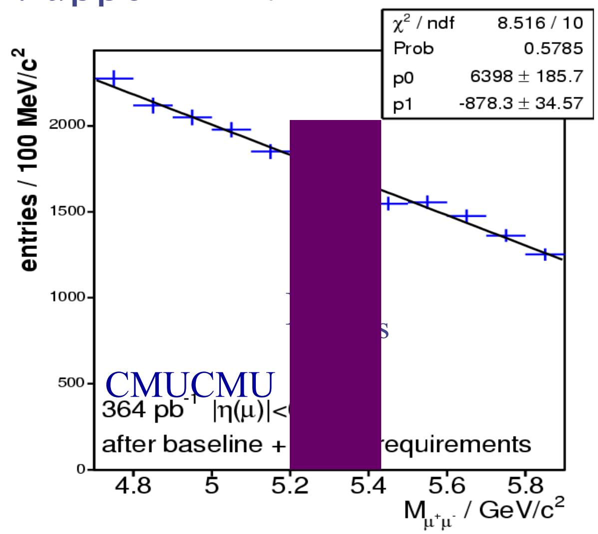
- \- Construct discriminant to select Bs signal and suppress bgd
- \- MC simulation for signal and mass sidebands for bgd estimate
- \- Optimize on minimum expected 90% C.L. upper limit

Normalization mode



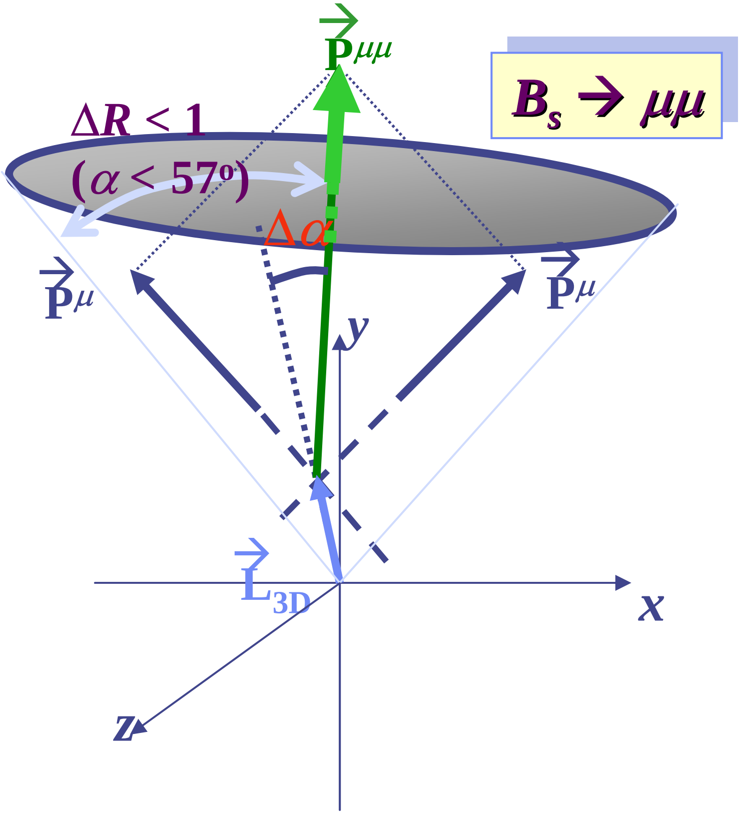
N(CMUCMU) = 1767±59
N(CMUCMX) = 698±39

Signal sample



N(CMUCMU) = 6242
N(CMUCMX) = 4908

$B_{s(d)} \to \mu^+\mu^-$ Signal vs. Bgd Discrimination



- μ+μ- mass, M: $|M-M_B|<60$ MeV/c^2 (2.5σ)

sidebands: 2×0.5 GeV/c^2 on the sides

signal: $|M-5279|<60$ MeV/c^2 (B_d^0) or $|M-5279|<60$ MeV/c^2 (B_s^0)

- Proper decay-length (λ): $$\lambda = \frac{cL_{3D}M}{|\vec{p}(B)|}$$

- Isolation (Iso): $$Iso = \frac{p_T(B)}{p_T(B) + \sum_i p_T^i(\Delta R_i < 1)}$$

(fraction of p_T from $B \to \mu\mu$ within $\Delta R = (\Delta\eta^2 + \Delta\phi^2)^{1/2}$ cone of 1)

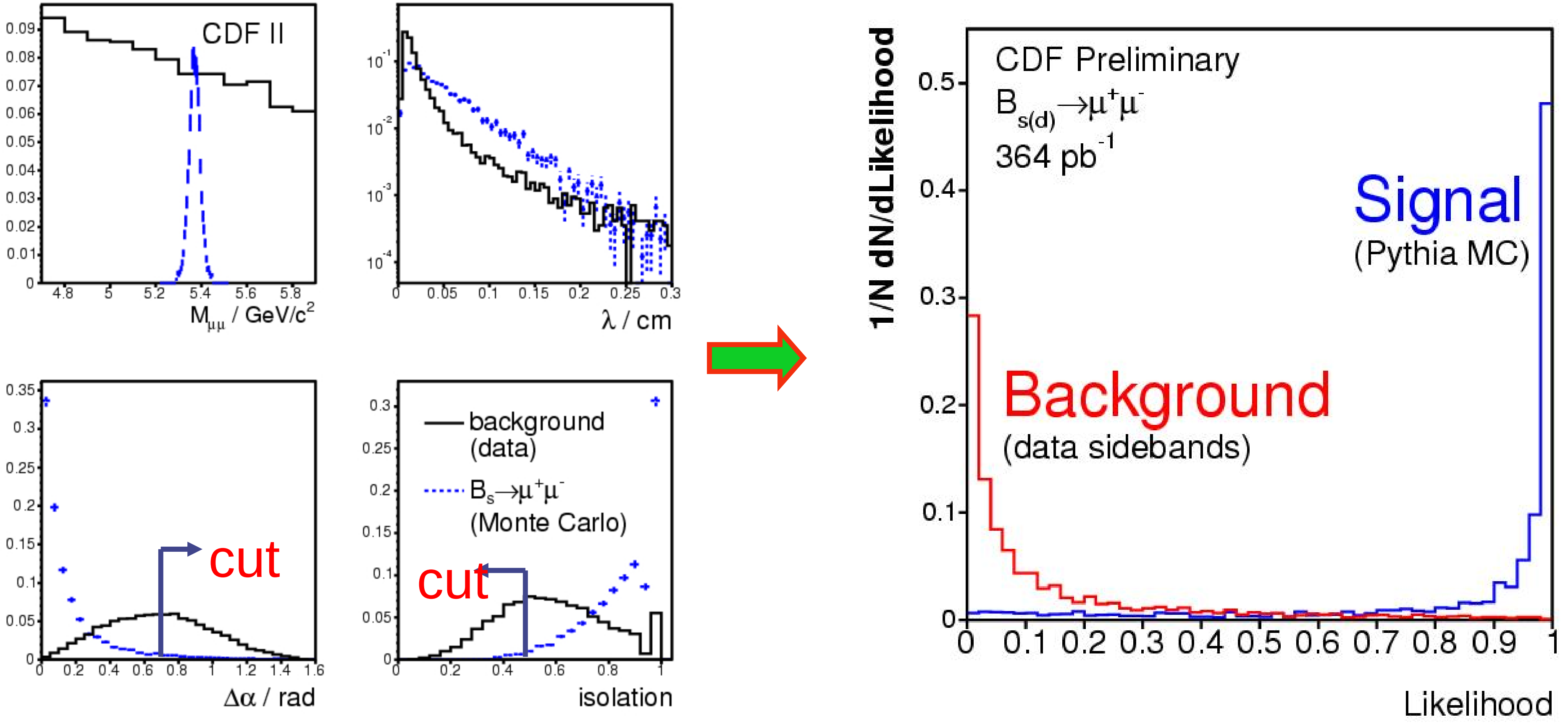
- "pointing ($\Delta\alpha$)": $$\Delta\alpha = \angle(\vec{p}(B) - \vec{L}_{3D})$$

(3D angle between B_s momentum and decay axis)

$B_{s(d)} \rightarrow \mu^+\mu^-$ Signal vs. Bgd Discrimination

☞ Construct Likelihood discriminant

$$LH = \frac{\prod_i P_s(x_i)}{\prod_i P_s(x_i) + \prod_i P_b(x_i)}$$

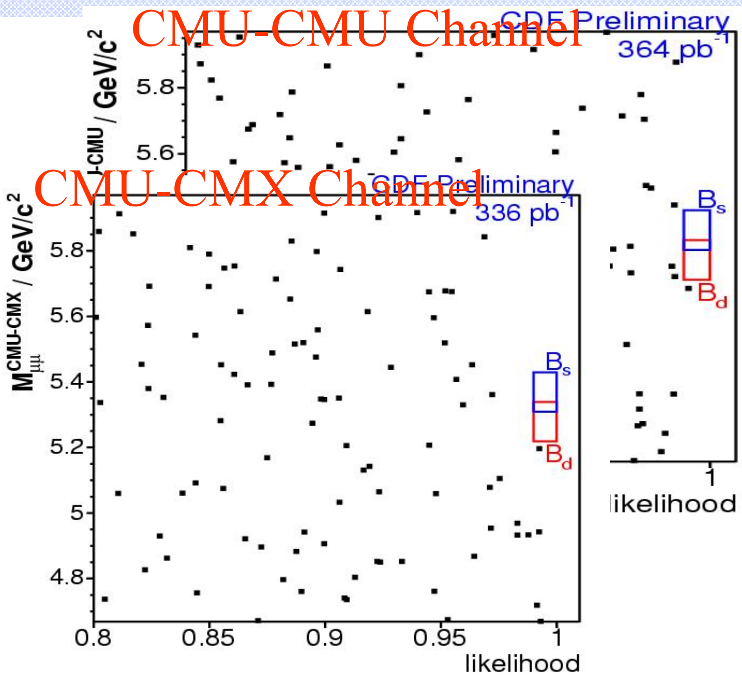


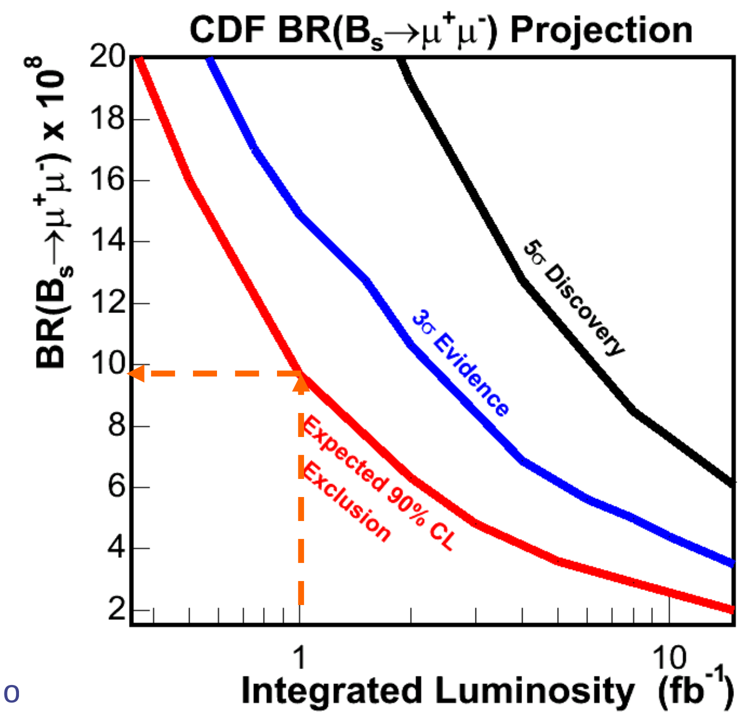
$B_{s(d)} \rightarrow \mu^+\mu^-$ Optimization and results

- Optimize using *a priory* expected upper limit (assumes no signal)
- Assume 1 fb-1 of data
  - **Optimal cuts: LH>0.99 and pT(B)>4GeV**
- For 360 pb^{-1} (combined for CMUCMU and CMUCMX)
  - $\langle BR^{90\%\ CL} \rangle = 2\times10^{-7}$ $N_{bg}=1.5\pm0.2$
  - Observe no events, consistent with expectations
  - $\rightarrow$ $Br(B_s \rightarrow \mu\mu) <$ **1.6×10^{-7} @ 90% CL**
    $Br(B_d \rightarrow \mu\mu) <$ **3.9×10^{-7} @ 90% CL**

Both CDF B_s and B_d results are $\times2$ better than the best published result

- **Expect $\times2$ improvement at 1 fb^{-1}**
  - **(high 10^{-8} region)**
  - **Even better when combined with D0**





$(B/B_s/B^+/\Lambda_b) \to \mu^+\mu^- h$

Yields (Belle/BaBar)

$B^+ \to ll K^+$	79 ± 10 ($253 fb^{-1}$)
$B^0 \to ll K^*$	82 ± 11 ($253 fb^{-1}$)
$B \to ll X_s$	68 ± 14 ($140 fb^{-1}$)

- $B^0 \to \mu^+\mu^- K^*$ and $B^+ \to \mu^+\mu^- K^+$ are already observed at B-factories
- $B_s \to \mu^+\mu^-\phi$ and $\Lambda_b \to \mu^+\mu^-\Lambda$ would be the first observations
- Shape analysis would be important to probe new physics

- The analysis strategy is very similar to that of $B \to \mu\mu$ (diff: use RAREB LXY)
  - Discriminating variables are essentially the same
  - Would try to explore box cuts first (not LH)

S. Farrington
R. Oldeman

Decay mode:	B^+	B^0	B_s
$N(B \to J/\psi h)$ ($260\ pb^{-1}$)	2270	981	95
BR($B \to \mu\mu h$) ($\times 10^{-7}$)	5.5 ♣ (Belle)	16.5 ♣ (Belle)	16.1 ♠ (hep-ph/0303246)
BR($B \to J/\psi(\mu\mu) h$) ($\times 10^{-5}$)	(5.88±0.25)	(7.70±0.45)	(55±20)
$\varepsilon(\mu\mu h)/\varepsilon(J/\psi h)$	0.78	0.69	0.69
Estimated S ($260\ pb^{-1}$)	16.6	14.6	1.94
Optimization not done yet, rough estimates $\to B_s \to \mu^+\mu^-\phi$ at $\sim 2\sigma$; B^+ and B^0 yields similar to Belle/BaBar; (limit on Λ_b at $0.3 Br_{SM}$?)			
$S/\sqrt{(S+B)}$ ($1\ fb^{-1}$) **PRELIM**	3	5	1.5-2

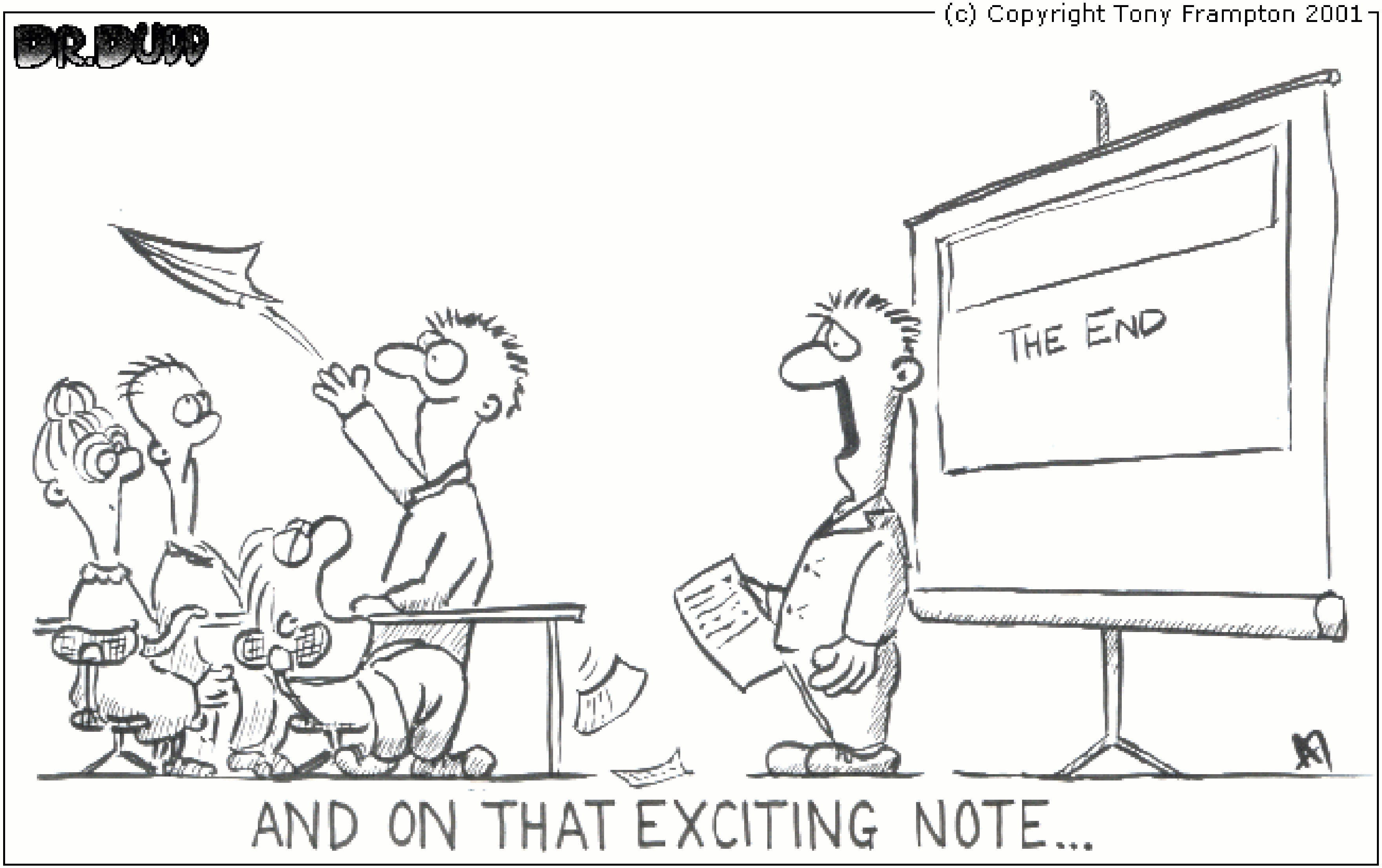
Summary

- $Br(B_s \to \mu\mu) < 1.6 \times 10^{-7}$ at 90% C.L.
- $Br(B_d \to \mu\mu) < 4 \times 10^{-8}$ at 90% C.L.
  - Both should improve ~×2 with 1 fb^{-1}
  - Prospect for $Br(B_s \to \mu\mu) \sim 1 \times 10^{-8}$ in Run II still holds
    - Vital for large tanβ supersymmetry
- $Br(D \to \mu\mu) < 2.4 \times 10^{-6}$ at 90% C.L. (69 pb^{-1})
  - Expect ~×10-20 improvement with 1 fb^{-1}

published

With 1 fb^{-1}:

- Expect to have sensitivity to $B^0 \to \mu^+\mu^- K^*$ and $B^+ \to \mu^+\mu^- K^+$ similar to B-factories (current)
- Expect first evidence of $B_s \to \mu^+\mu^- \phi$ and first limit on $\Lambda_b \to \mu^+\mu^- \Lambda$
- Substantial improvements in charm→llh decays and $D^0 \to K^+\pi^-$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DR.DUDD
THE END
AND ON THAT EXCITING NOTE...

BACKUP SLIDES

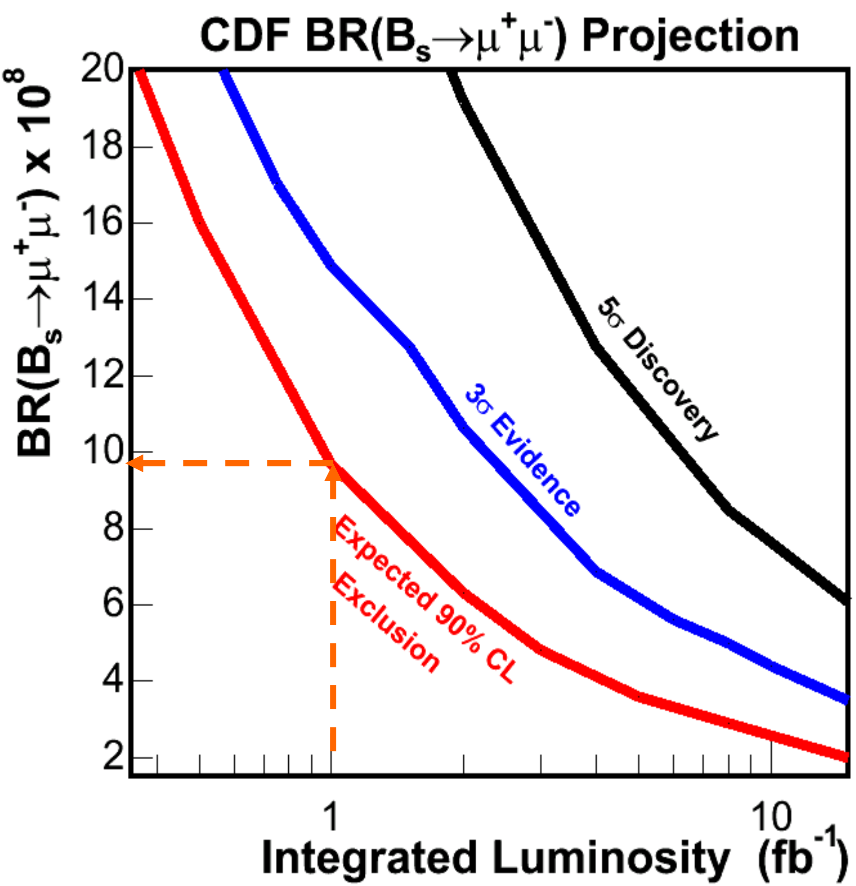
$B_s \rightarrow \mu\mu$ Prospects

Simplistic: no improvement to analysis

→scale N_{bg} and N_{B+} linearly with Lumi

→ recalculate

→ at best ~3×10^{-8} at 90% CL



- Optimistic:
~ 1/Lumi
  - Additional handles on bgd exist:
    tighter muon ID (require CMP)
    calorimeter isolation
    additional 2D pointing
    use mass resolution model in LH
  - Combine with D0

→BR($B_s\rightarrow\mu\mu$) ≈ 1×10^{-8} at 90% CL is possible within Run II (by 09?)

- Can be measured at SM level by CMS at LHC after 2-3 years of data taking (by 10?)

Triggers used

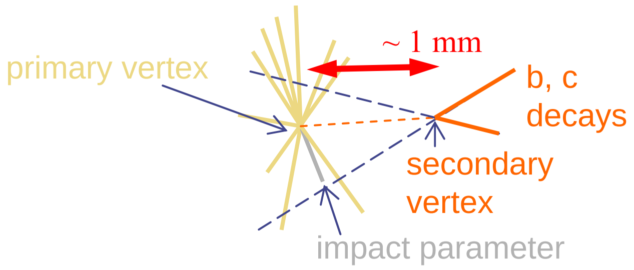
All are input to the various Level-3 triggers
That use the offline quality information

Dimuon trigger

- p_T>1.5GeV, $|\eta|$<0.6
  p_T>2GeV, 0.6<$|\eta|$<1
- p_T, ϕ, muon ID used to cut on tracks
- Used for ψ,Y,B$\rightarrow\mu\mu$(+X)

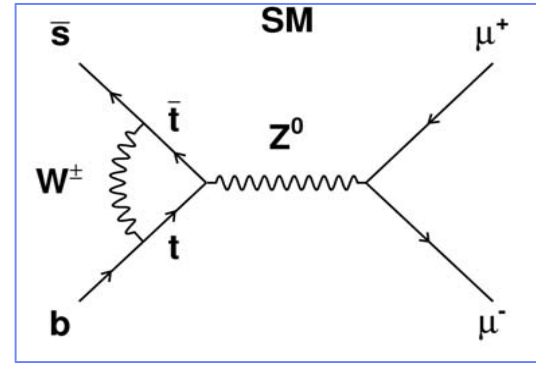
Two Track Trigger

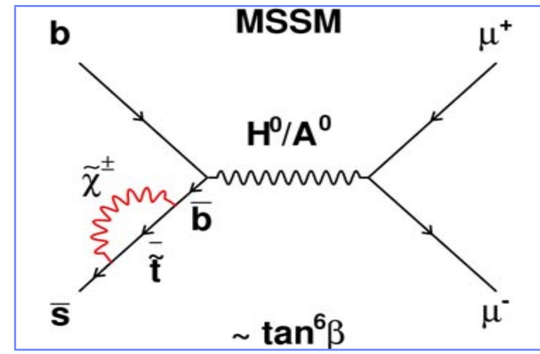
- p_T>2GeV, $|\eta|$<1
- p_T, ϕ, d_0 info used to cut on 2 tracks
- Used for: B,D$\rightarrow$hadrons ; D$\rightarrow\mu\mu$



$B(D)\rightarrow\mu\mu$: Theoretical motivations. Current limits.

- Flavor Changing Neutral Current. Loop contribution only in SM.
  - $Br_{SM}(B_s\rightarrow\mu^+\mu^-)=(3.4\pm0.5)\times10^{-9}$
  - $Br_{SM}(B_d\rightarrow\mu^+\mu^-)=(1.00\pm0.14)\times10^{-10}$ (hep-ph/0303060)
  - $Br_{SM}(D^0\rightarrow\mu^+\mu^-)\sim3*10^{-13}$ (GIM suppressed)
- Only upper experimental limit exists:
  - $Br_{exp}(B_s\rightarrow\mu^+\mu^-)<2.0\times10^{-6}$ 90% C.L. CDF RunI @100/pb.
  - $Br_{exp}(B_d\rightarrow\mu^+\mu^-)<1.6\times10^{-7}$ 90% C.L. Belle '03 @78/fb.
  - $Br_{exp}(D^0\rightarrow\mu^+\mu^-)<4.1(4.2)*10^{-6}$ 90% C.L. BEATRICE(E771)



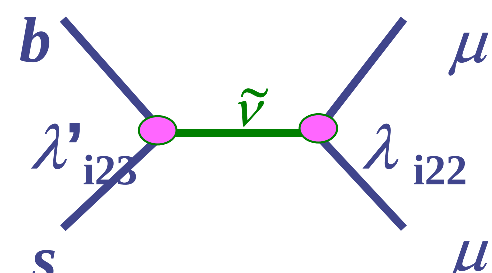


- Limits are far away from the SM value: can test for a possible new physics.

mSUGRA,SO(10)

> - MSSM: $Br(B\rightarrow\mu^+\mu^-)$ enhanced by $\tan\beta>10$ terms $\sim\tan^6\beta$. Up to 100 over the SM prediction.
> - R-parity violating models give tree level contributions. Not heavily constrained by other observables.

- Can be seen in Run2 (esp. $B_s\rightarrow\mu\mu$)

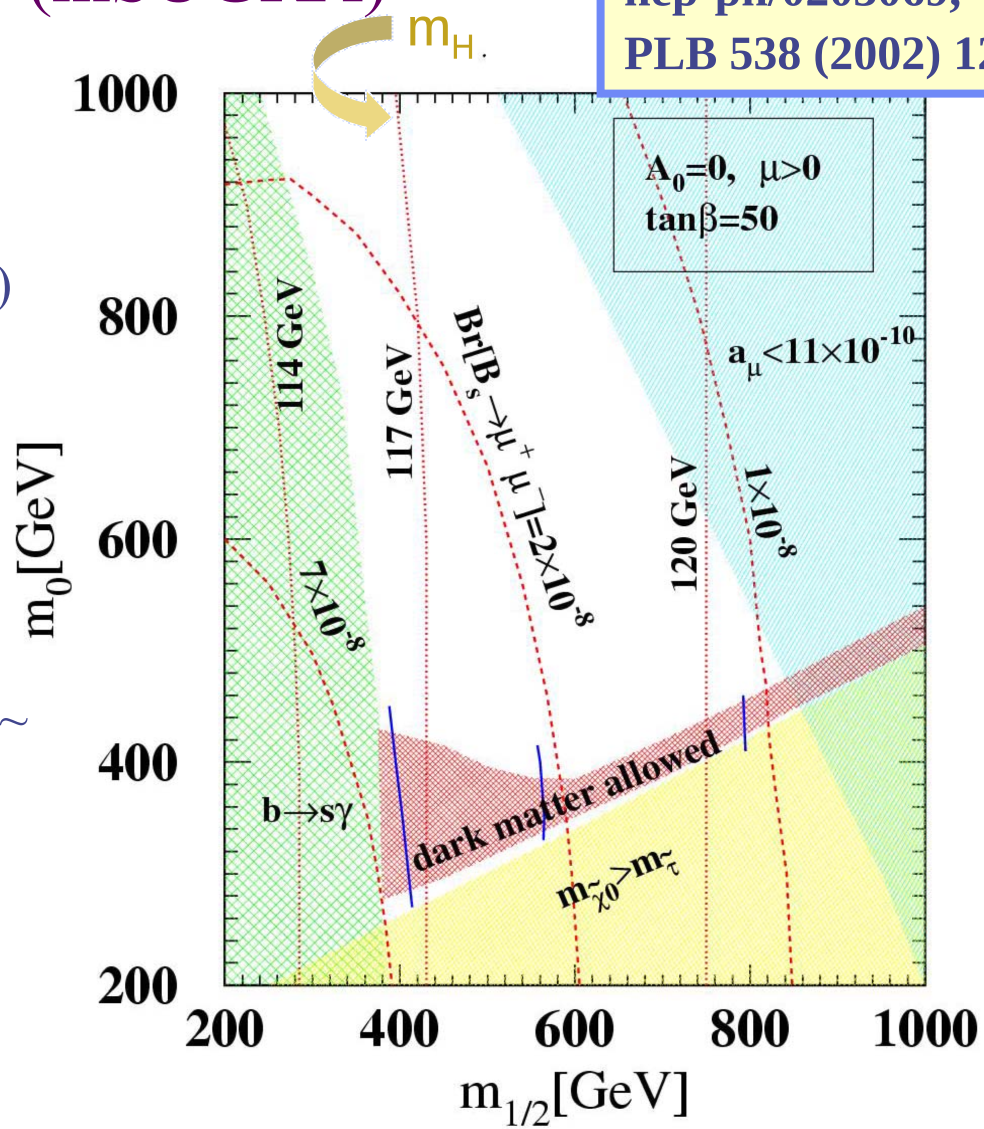


RPV

- Other models enhance less. E.g., universal extra dimensions. Up to +70% for $B_s\rightarrow\mu^+\mu^-$

Motivations: $B_s \rightarrow \mu^+\mu^-$ (mSUGRA)

R. Arnowitt *et al.*, hep-ph/0203069, PLB 538 (2002) 121

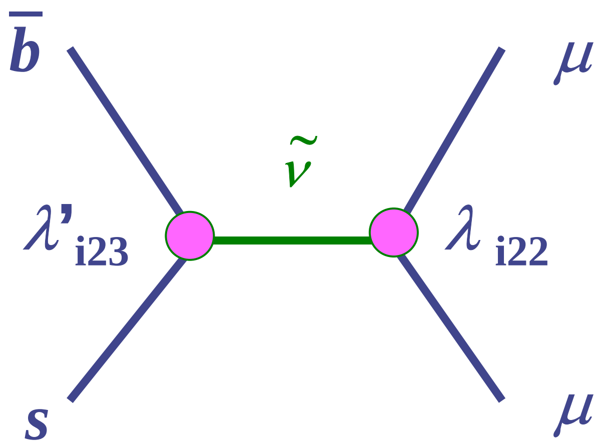


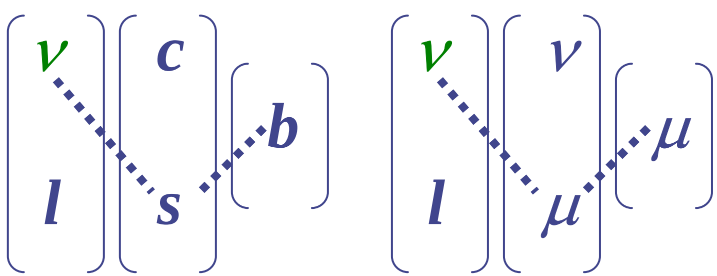
- Overlap with measured δa_μ (BNL) in mSUGRA parameter space.
- Overlap with dark matter=LSP allowed region.
- Eliminate large parameter space (~ all for $\tan\beta>40$), with $Br(B_s\rightarrow\mu^+\mu^-)\sim10^{-8}$ in Run2

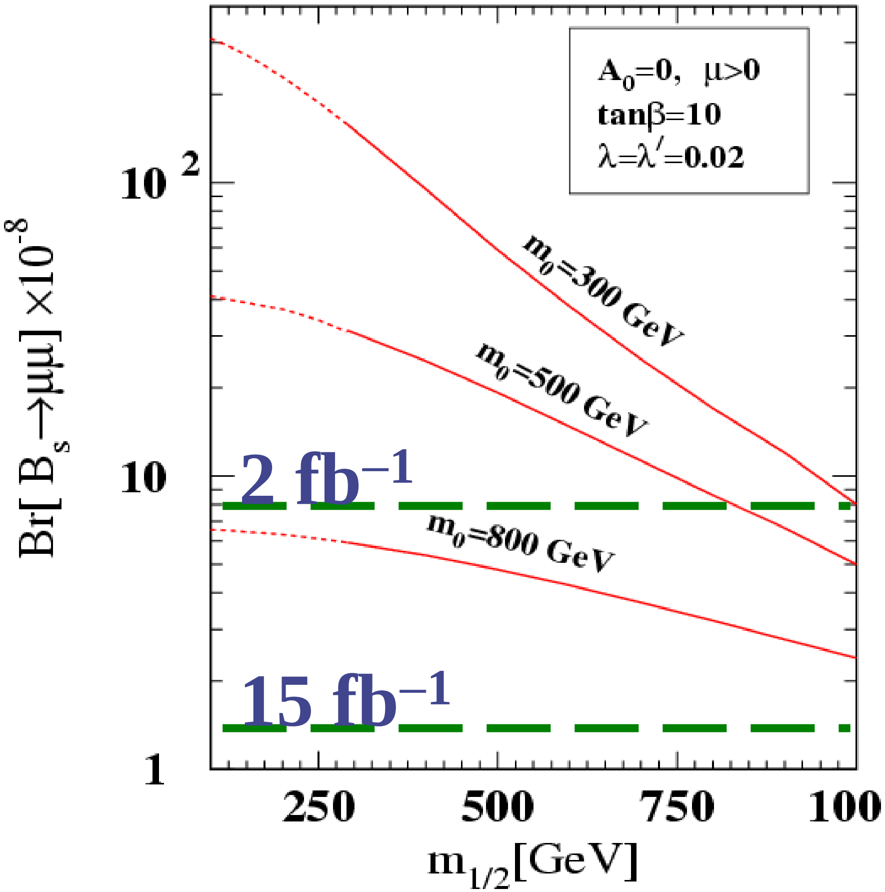
R_P Violation: *Br* vs. $m_{1/2}$

R. Arnowitt *et al.*, hep-ph/0203069, PLB 538 (2002) 121

e.g., $W_{TRPV} = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k$



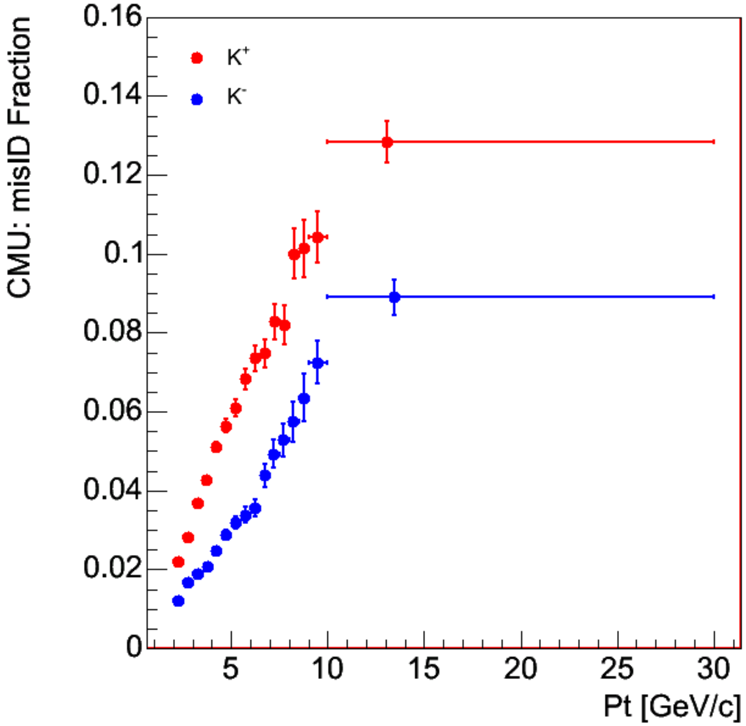




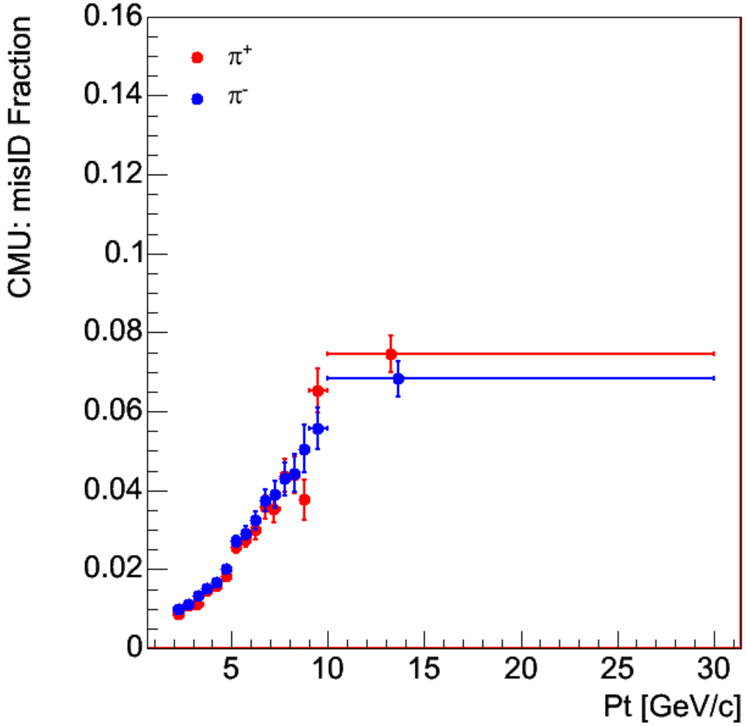
Muon fake rates: CMU

- E. Berry, I. Furic, et al.

Kaons

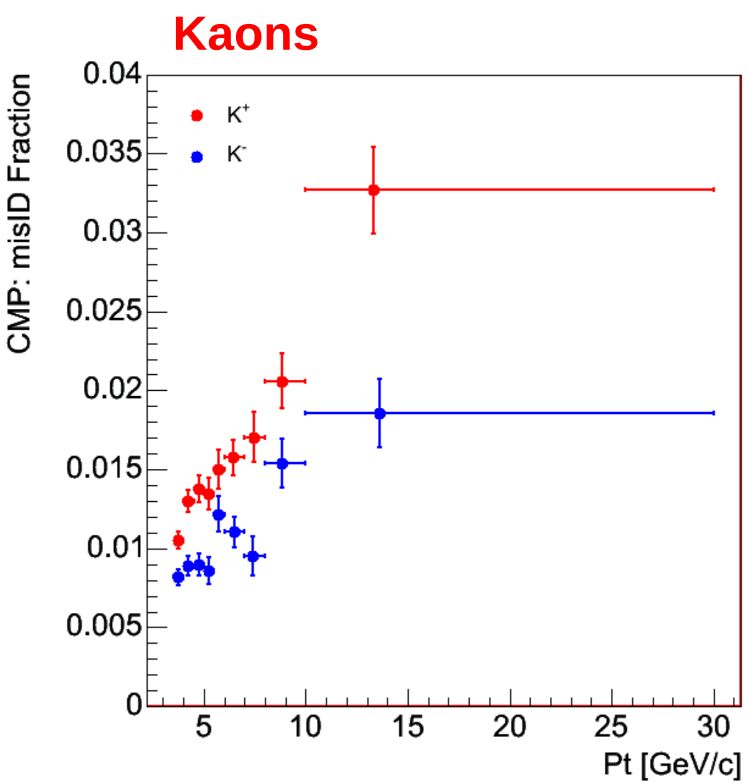


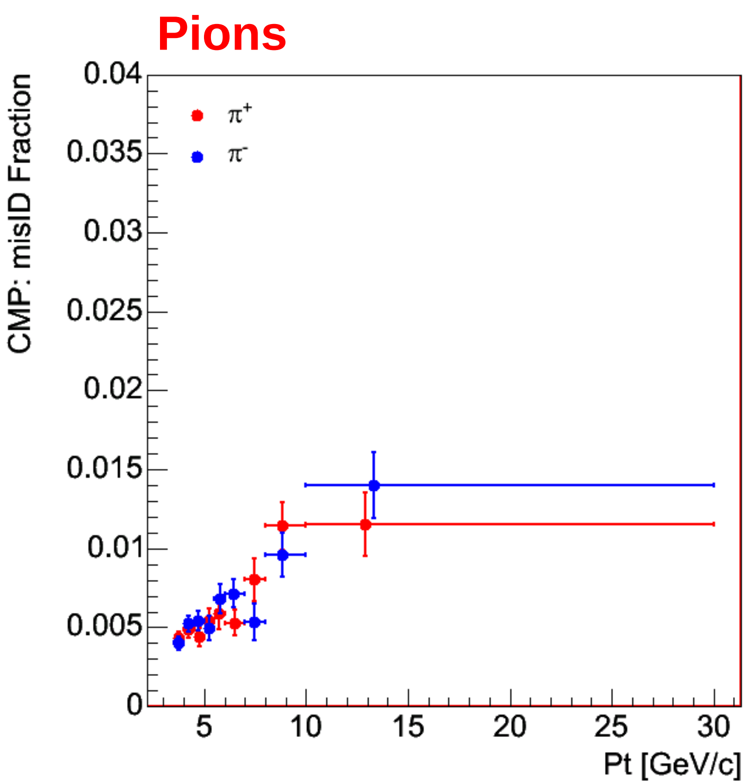
Pions



Muon fake rates: CMP

- E. Berry, I. Furic, et al.





Muon fake rates: CMX

- E. Berry, I. Furic et al.